

Enabling and Expanding HCCI in PFI Gasoline Engines with High EGR and Spark Assist

**Robert M. Wagner, K. Dean Edwards, C. Stuart Daw,
Johney B. Green Jr., Bruce G. Bunting**

**Fuels, Engines, and Emissions Research Center
Oak Ridge National Laboratory**

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Outline

- **Overview**
- **Background**
- **Setup and experiments**
- **Characterization of cyclic dispersion**
- **Short term prediction for control**
- **Other observations**
- **Conclusions**
- **Future**

Overview

Motivation

- **HCCI stability and control continue to be major issues to the implementation of HCCI (although progress is being made).**
- **Conventional combustion will probably still be used for some operating conditions.**

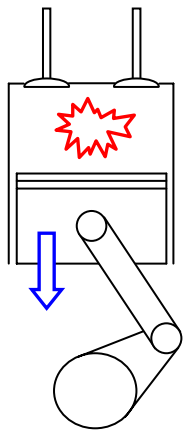
Approach

Make use of technology from nonlinear dynamics community as well as previous experience to diagnose and control HCCI.

Cyclic Variability Diagnostic & Control

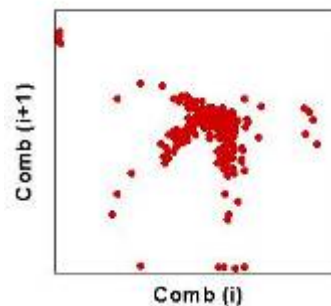
Measurement

- In-cylinder pressure
- Ionization
- Crank shaft acceleration
- Other



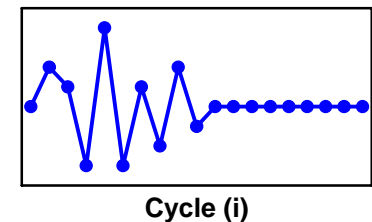
Analysis

- Pattern recognition
- Prediction
- Modeling



Control

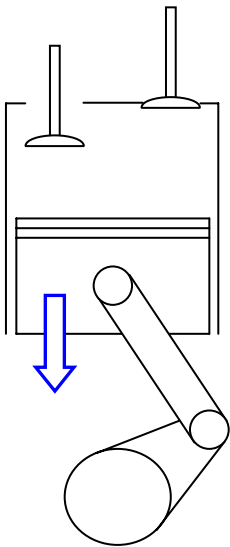
- Avoid certain states
- Short- and long-time scale feedback perturbations (e.g., fuel, spark, etc.)
- Pro-active rather than re-active



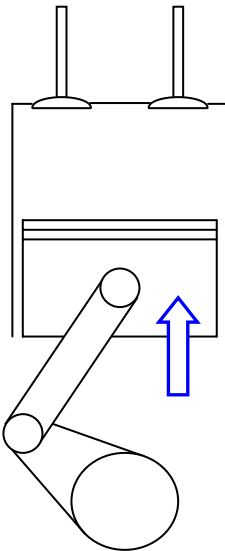
Example from Lean SI Combustion Experience

Under dilute conditions, instabilities arise due to feedback from stochastic (turbulence/mixing) and deterministic (residual gas) processes

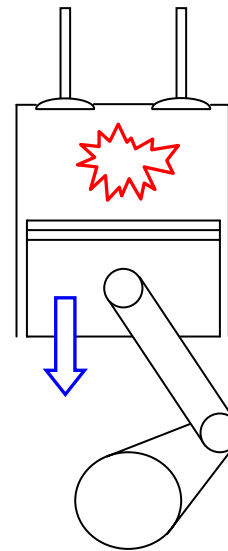
Fuel / Air IN



1. Intake



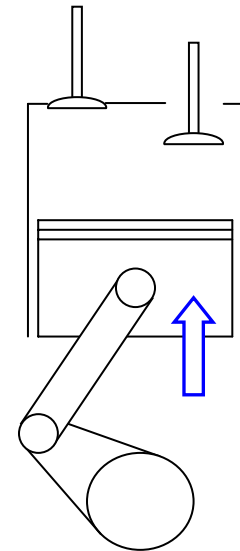
2. Compression



3. Power

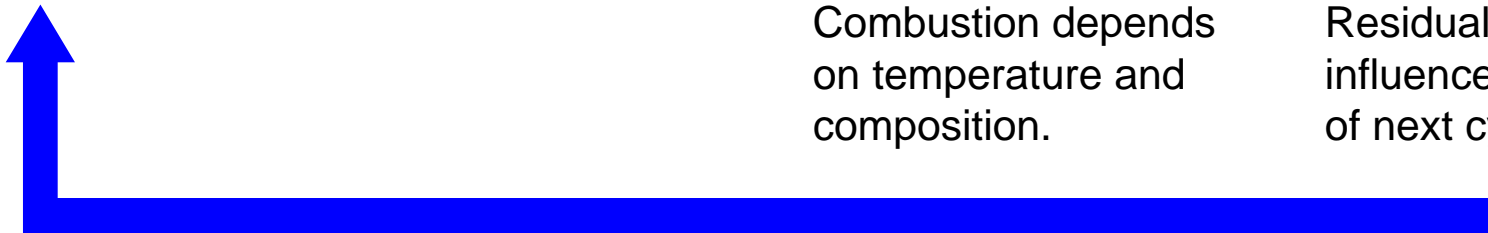
Combustion depends
on temperature and
composition.

Exhaust OUT



4. Exhaust

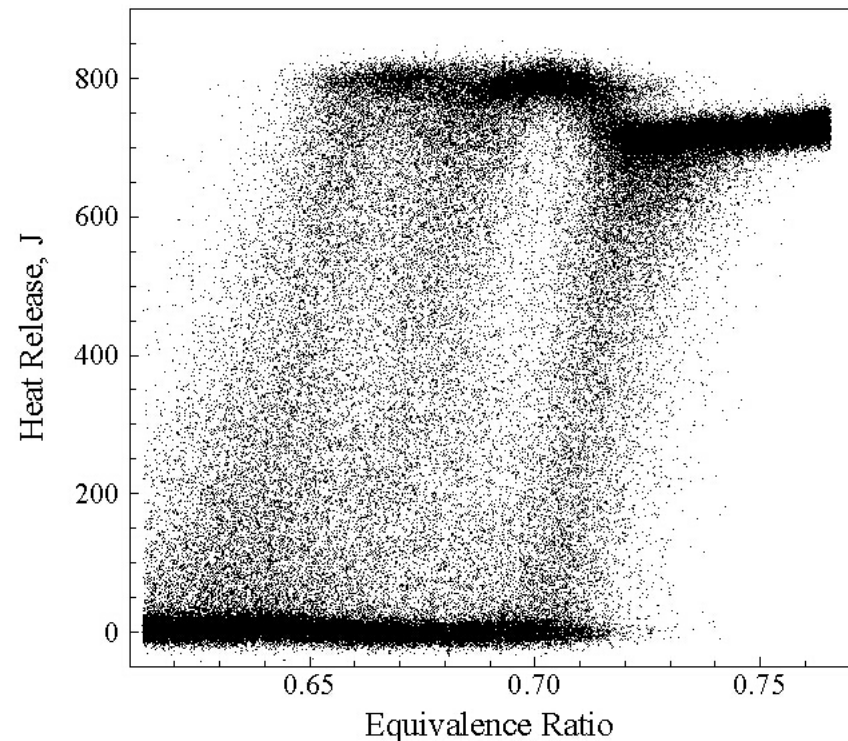
Residual gas
influences beginning
of next cycle.



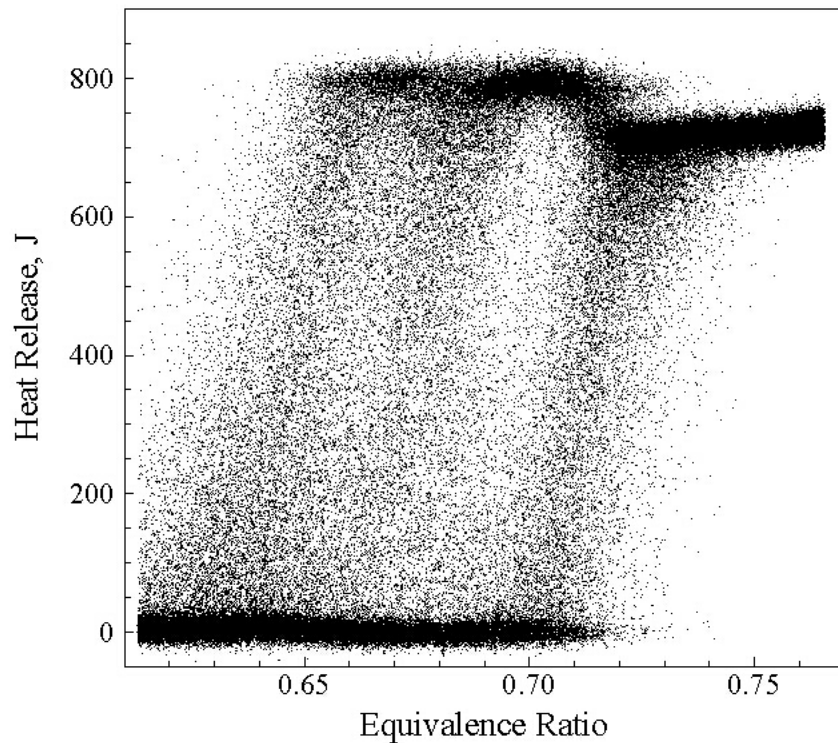
Cycle-to-Cycle Coupling

Cycle-to-cycle variations associated with lean SI (and HCCI) combustion are complex but tractable

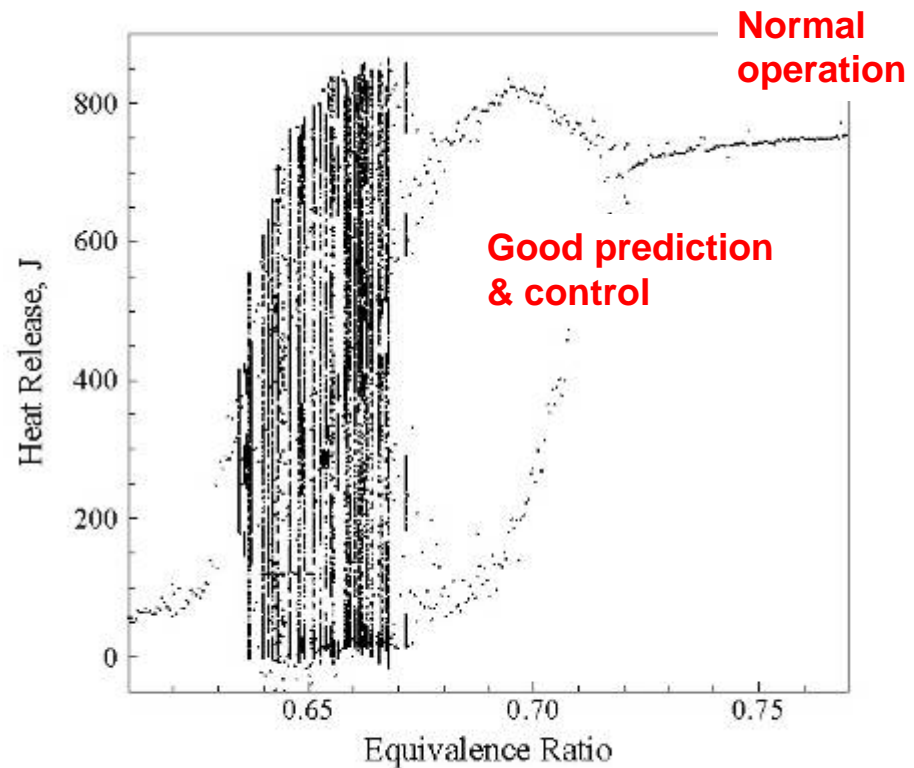
- **Combustion instability increases near lean limit**
- **Instabilities develop as a period-doubling bifurcation sequence due to nonlinear flame dynamics**
- **Deterministic (predictable) component dominated by prior-cycle residual gas (similar to high EGR HCCI)**
- **Stochastic (random) component (from mixing, turbulence, etc.) increases complexity but doesn't eliminate predictability**



Deterministic component is revealed through construction/analysis of special maps

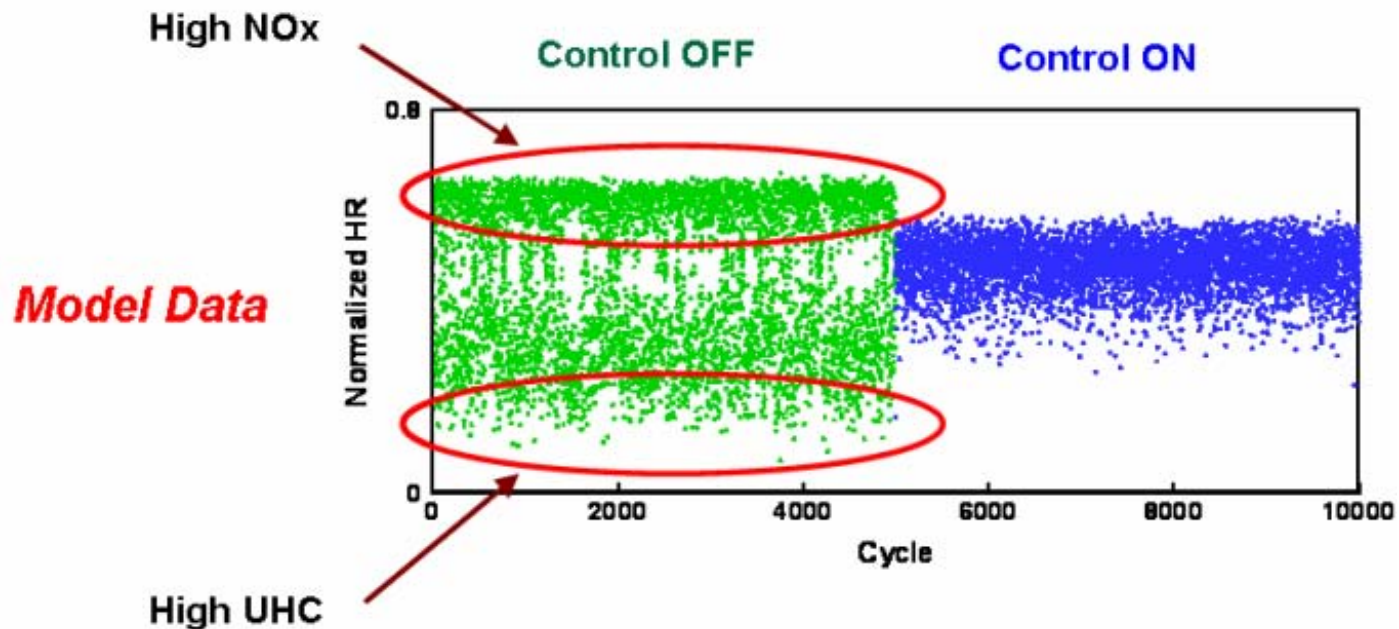


Experimental Data



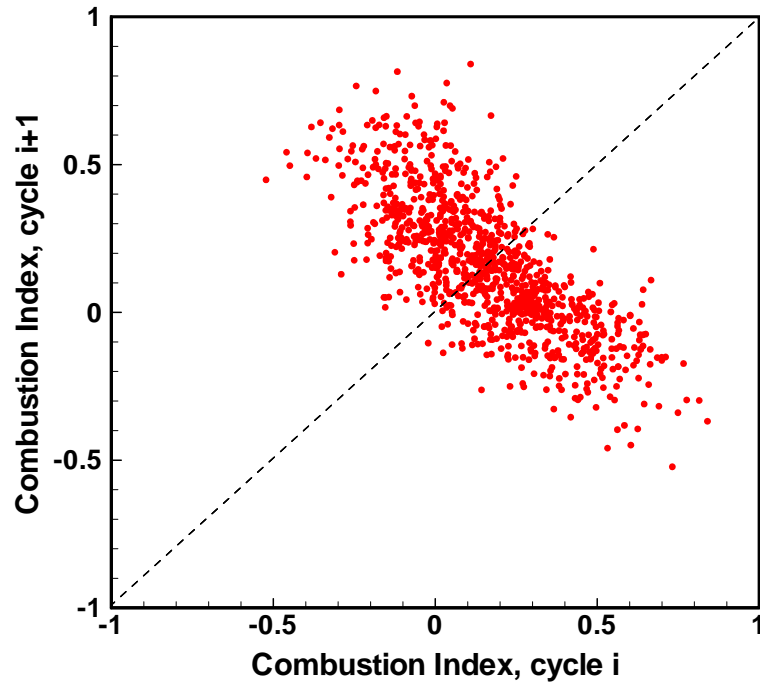
Map Reconstruction

Understanding patterns has been shown to reduce cyclic variability and maintain leaner operation in gasoline and NG engines

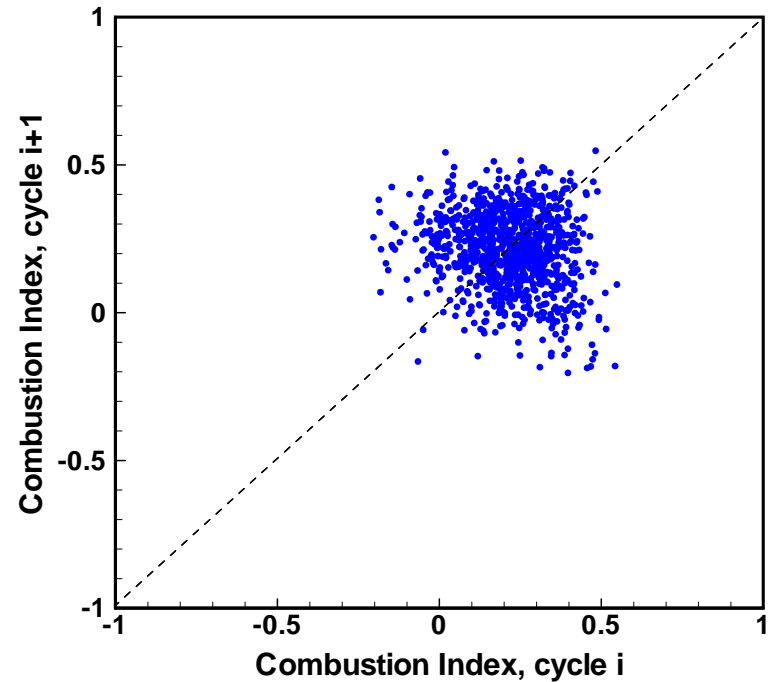


Control reduces harmful excursions with no increase in fuel usage.

Real-time control of lean cycle-to-cycle combustion instabilities was demonstrated on a Ford Grand Marquis vehicle in a joint Ford-ORNL project



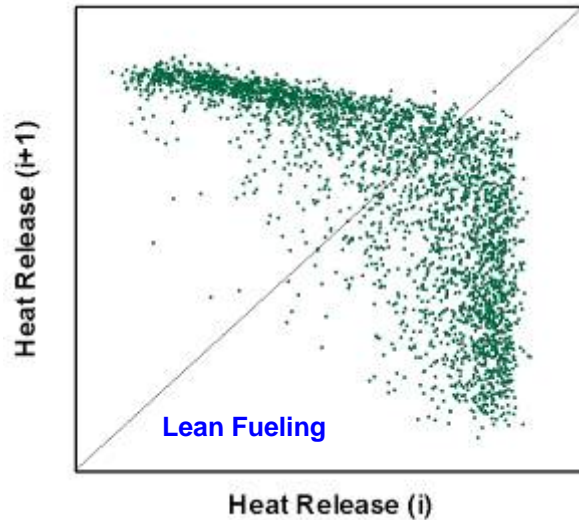
Uncontrolled



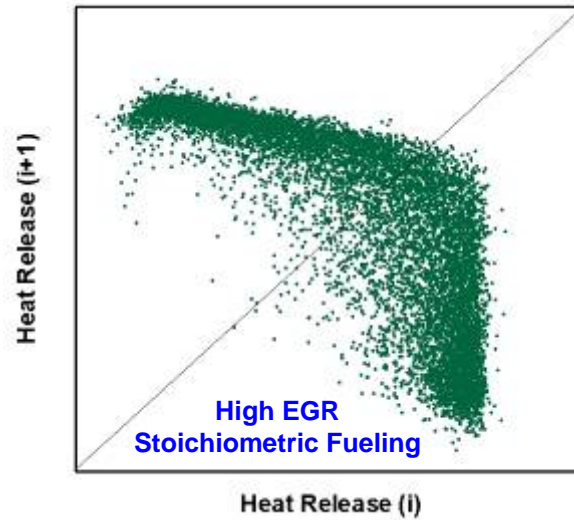
Controlled

SAE 2001-01-0257, U.S. Patent 5,921,221

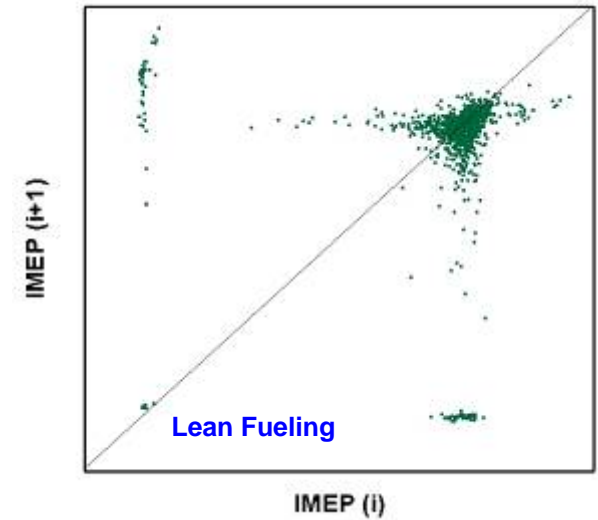
Similar patterns have been observed in many different engines



GM Quad-4
(Gasoline, 4-stroke, 9.2 cm bore)
Oak Ridge National Laboratory



Ford Zetec
(Gasoline, 4-stroke, 8.5 cm bore)
University of Missouri-Rolla



Cooper-Bessemer
(NG, 2-stroke, 36.0 cm bore)
Colorado State University

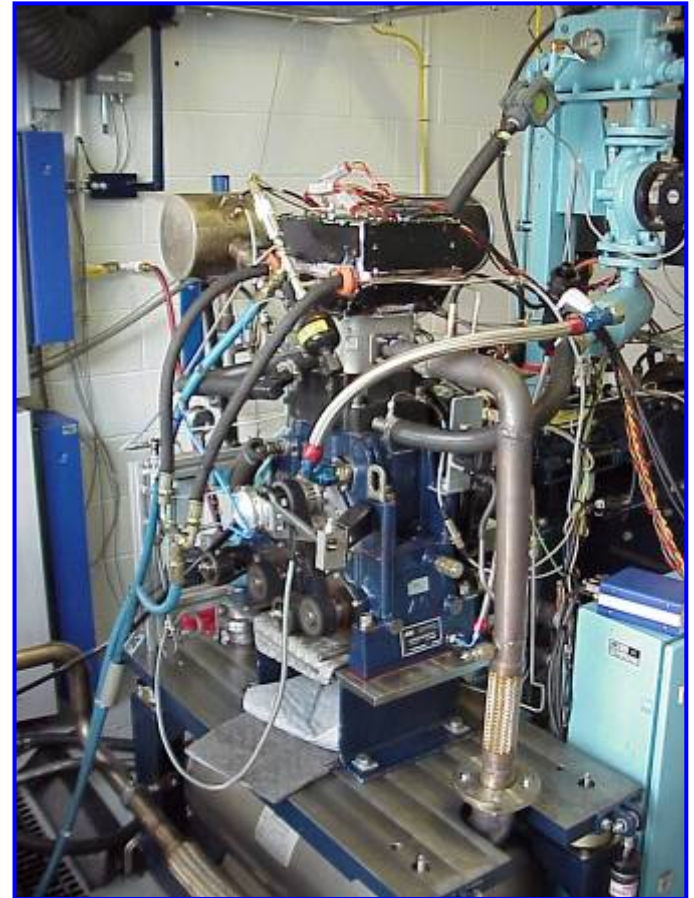
There are good reasons to expect such patterns in HCCI

- High EGR is often a major feature
- The transition between propagating flame and HCCI is very nonlinear
- Nonlinear transitions typically involve bifurcations (instabilities)

Transition to Spark Assisted HCCI Combustion

Experimental Platform

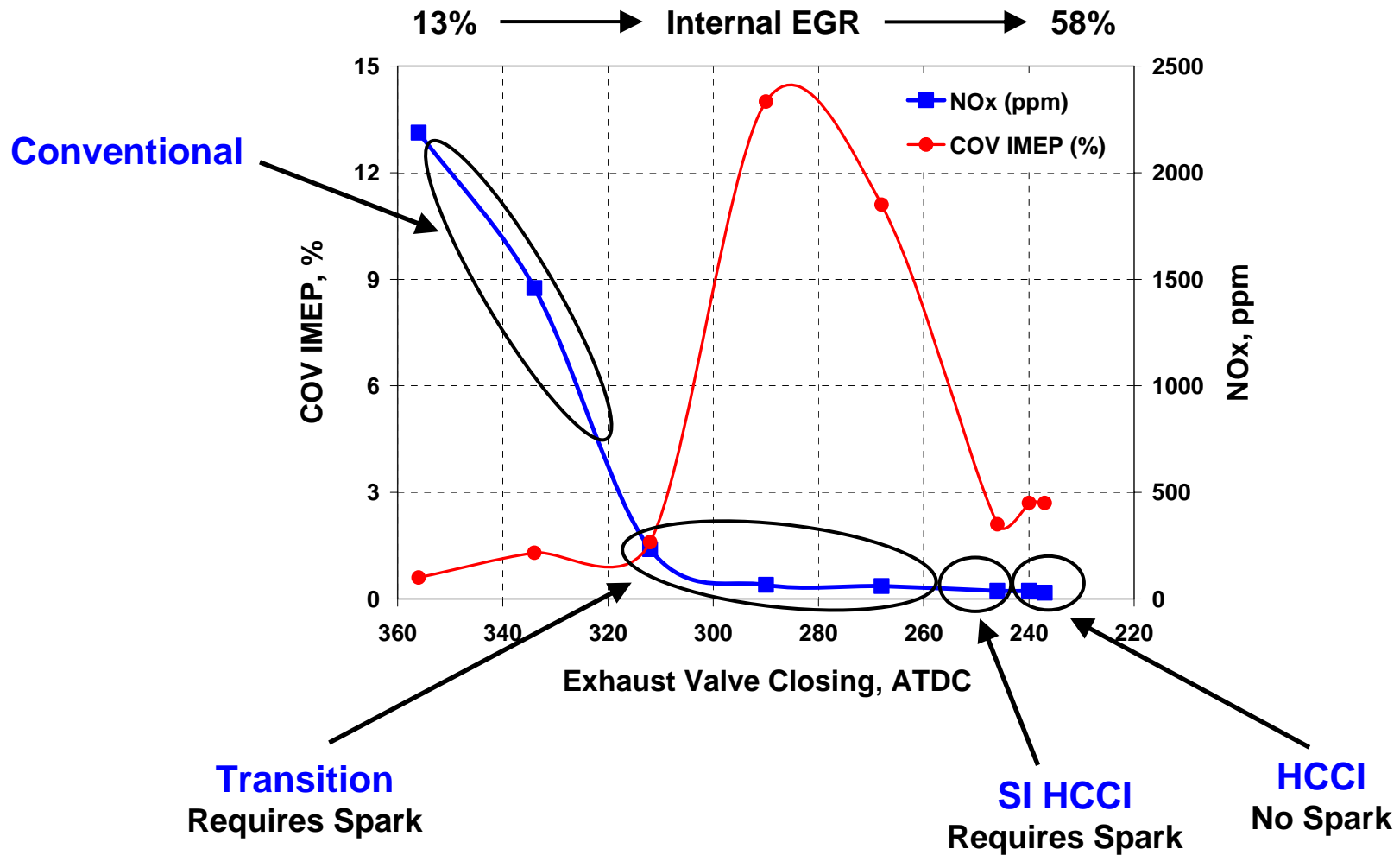
- **AVL Powertrain single-cylinder research engine**
 - 0.5 L, 11.34 CR
 - Port fuel injection
 - Spark ignition
 - Fully variable valve actuation
- **Capable of HCCI, mixed mode, and conventional operation**
- **HCCI controlled by intake and exhaust valve timing and lift**
 - Early exhaust closing – negative overlap strategy
 - Internal EGR increased to transition to HCCI



Experiments To Date

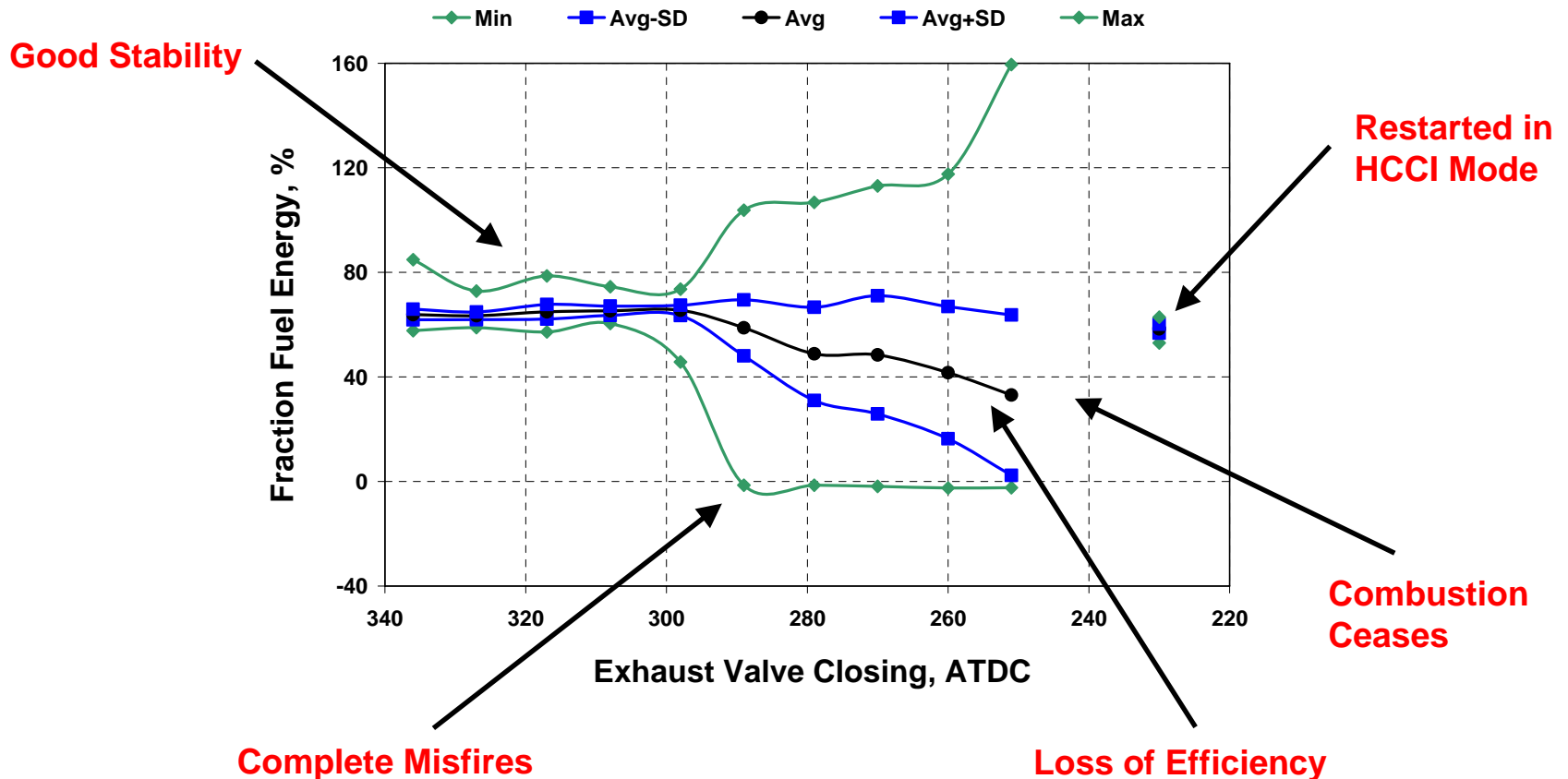
- **All experiments performed at near stoichiometric conditions.**
- **Internal EGR sweeps for...**
 - Three speed-load combinations (1200 rpm, 2.5 bar; 1600 rpm 3.0 bar; 2400 rpm, 4.5bar).
 - Two spark timings at 1600 rpm, 3.0 bar.
 - Three coolant temperatures at 1600 rpm, 3.0 bar.
- **Mode transition experiments.**
 - Conventional to HCCI to conventional at 1600 rpm, 3.0 bar.

Transition to HCCI with internal EGR reveals modes with low NOx emissions



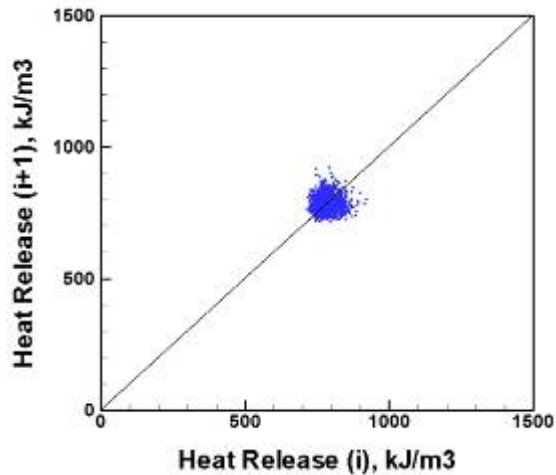
Not shown is discontinuity between transition range and SI HCCI

Stability and efficiency deteriorates with increasing EGR until HCCI conditions reached

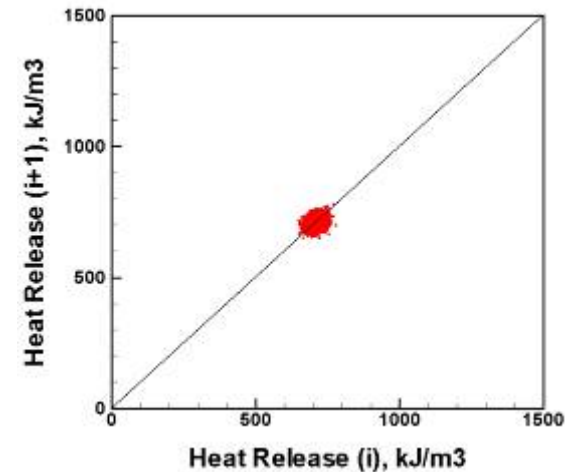


Cycle-to-cycle variations exhibit non-random structure during transition

Conventional SI



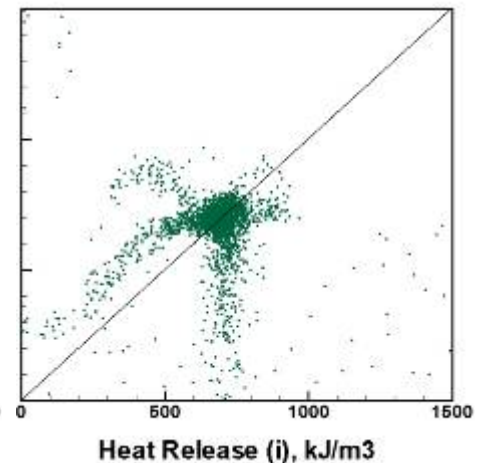
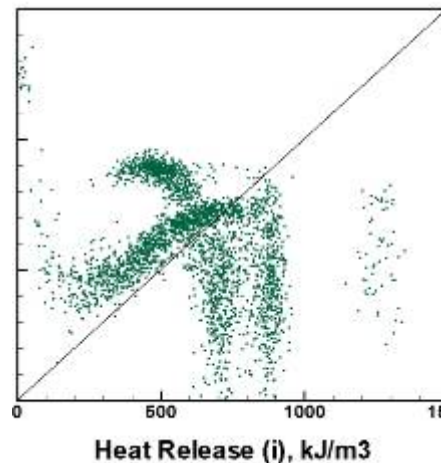
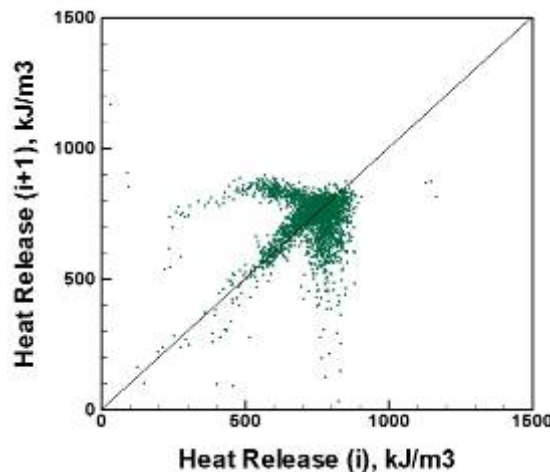
HCCI



Increasing EGR

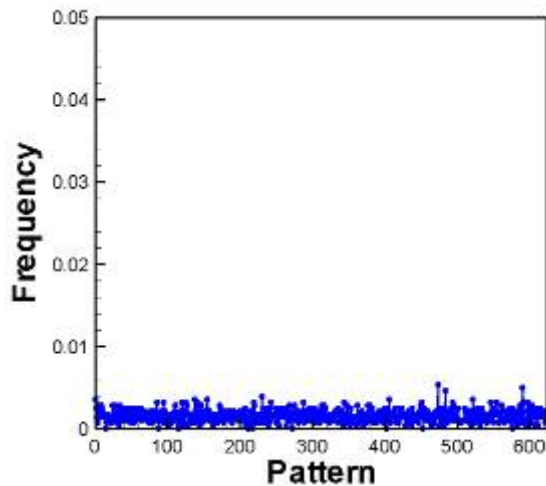


Transition



Symbol based analysis identifies re-occurring patterns in the heat release time series

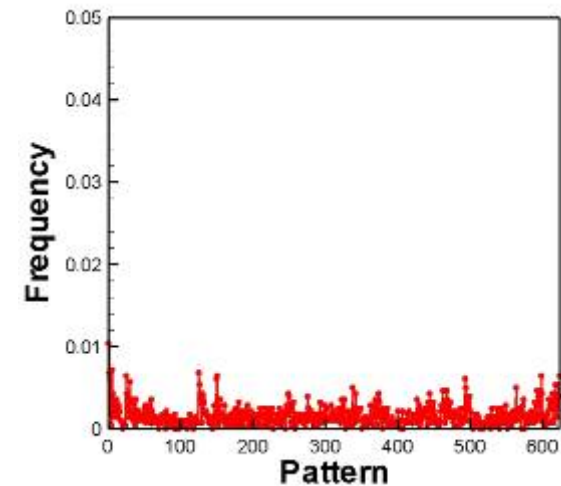
Conventional SI



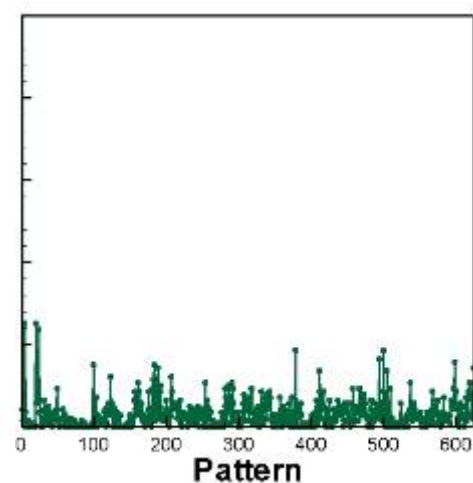
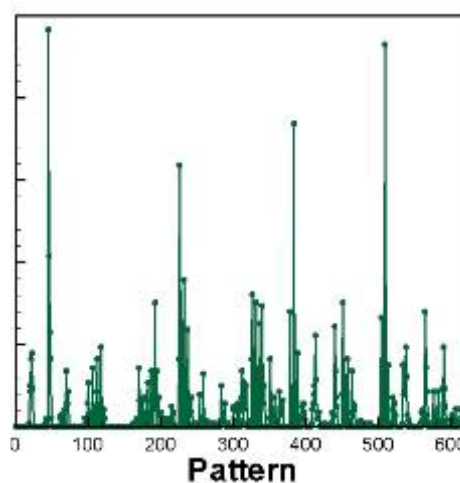
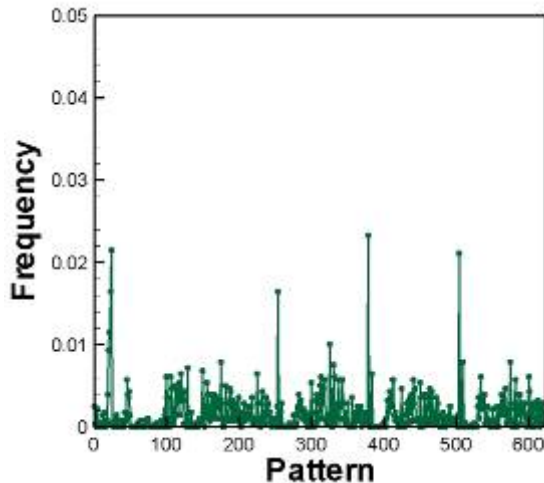
Increasing EGR



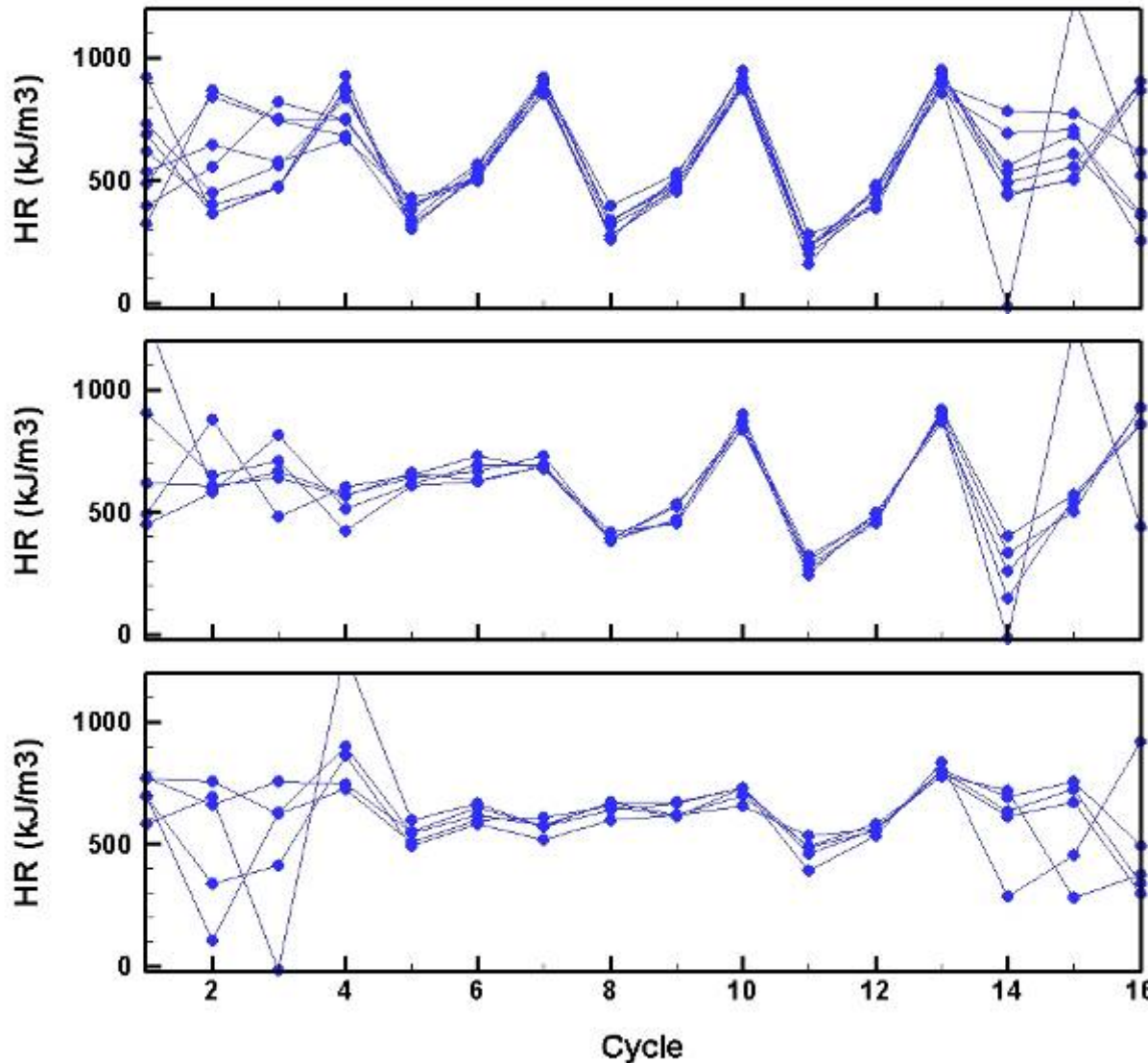
HCCI



Transition



Example patterns observed in the engine



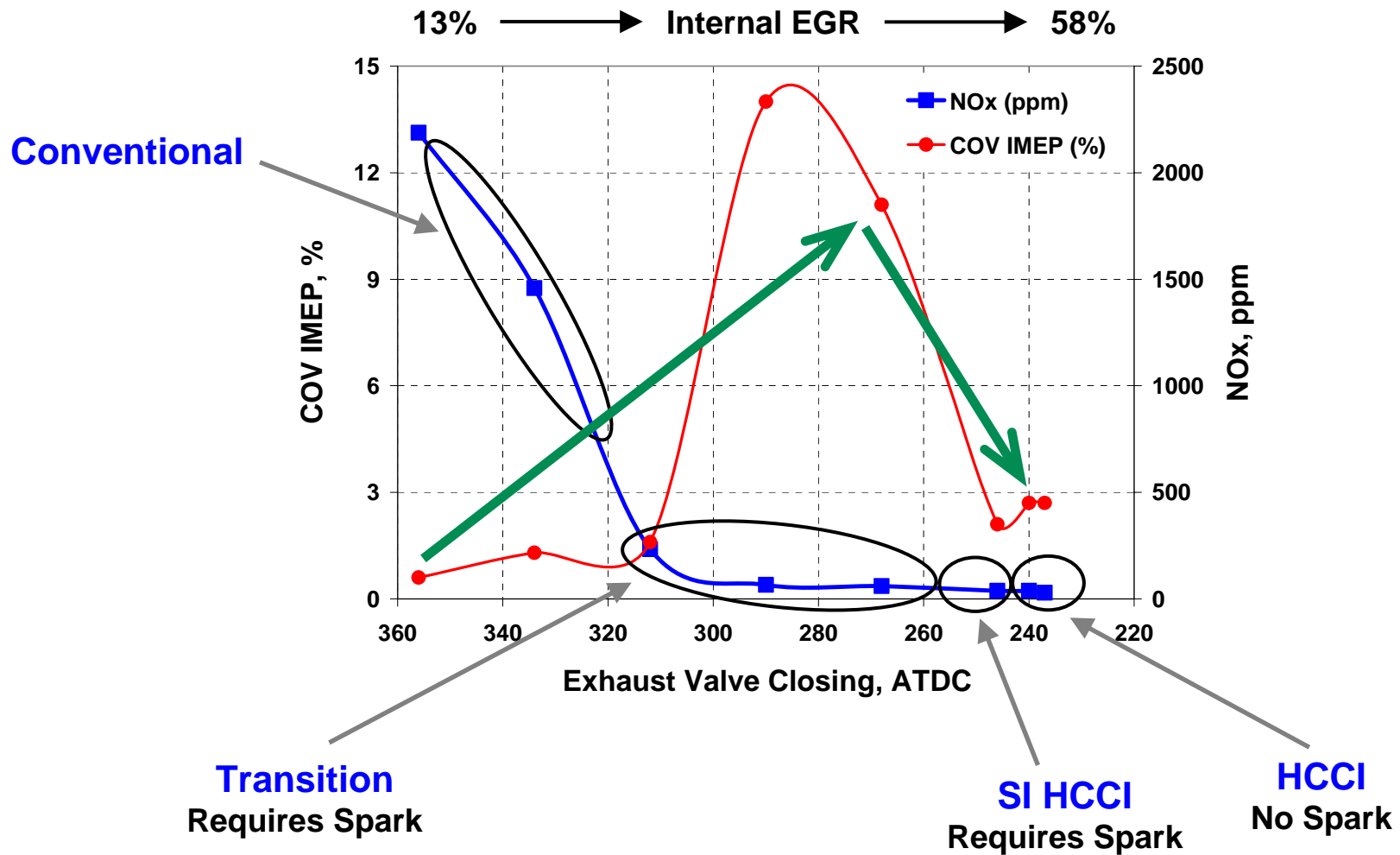
Engine frequently visits 3-state pattern in transition region

Engine oscillates near single value before entering more complicated pattern

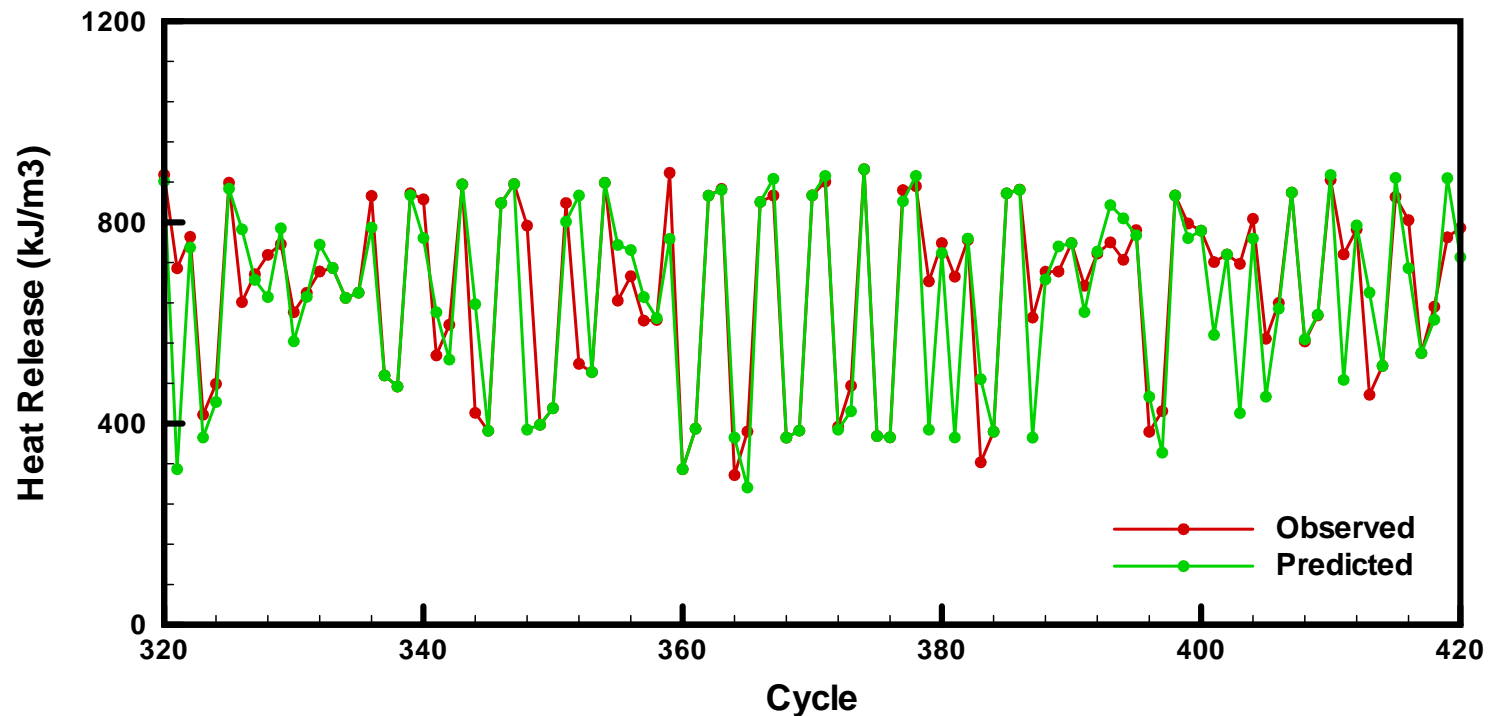
Engine frequently oscillates near single value (control point)

Why do we care about intermediate region
between conventional SI and HCCI?

SI to HCCI operation requires 2-step process through unstable transition region



Preliminary result indicate cycle dynamics can be predicted in the transition region (AVL engine)



Predictor trained on experimental data acquired on different day.

Other Observations

- **Combustion becomes increasingly unstable and ceases as conditions approach HCCI (i.e., a discontinuity exists).**
- **“Strength” of discontinuity observed during transition was influenced by speed and load.**
- **Fast transition from SI to HCCI required a 2-step process, whereas transition from HCCI to SI could be accomplished in 1 step.**
- **Cyclic dispersion patterns were very repeatable day-to-day.**

Conclusions

- **The transition between regular SI and HCCI using internal EGR progresses through an ordered, reproducible bifurcation sequence**
- **The bifurcation patterns are relatively low-dimensional (3-4) and can be easily monitored**
- **The actual trajectories in the transition region are complex (high period or deterministic chaos with noise), but they are short-time predictable**
- **Nonlinear pattern recognition and feedback control strategies are likely to be useful for improving HCCI utilization**

Where do we go from here?

- **Evaluate techniques with other types of HCCI engines**
- **Develop diagnostic indices and select appropriate sensors for tracking the patterns in real engines in real time**
- **Apply combustion and engine models to explain what is going on in the transition process (physics, chemistry)**
- **Develop low-order engine and systems models and strategies that can be used for real time analysis of stability, prediction, control**
- **Identify and/or develop more optimal feedback parameters**